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Modeling approaches to inform travel-related policies for COVID-19 containment: A scoping review and future directions

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ABSTRACT

Background: Travel-related strategies to reduce the spread of COVID-19 evolved rapidly in response to changes in the understanding of SARS-CoV-2 and newly available tools for prevention, diagnosis, and treatment. Modeling is an important methodology to investigate the range of outcomes that could occur from different disease containment strategies.

Methods: We examined 43 articles published from December 2019 through September 2022 that used modeling to evaluate travel-related COVID-19 containment strategies. We extracted and synthesized data regarding study objectives, methods, outcomes, populations, settings, strategies, and costs. We used a standardized approach to evaluate each analysis according to 26 criteria for modeling quality and rigor.

Results: The most frequent approaches included compartmental modeling to examine quarantine, isolation, or testing. Early in the pandemic, the goal was to prevent travel-related COVID-19 cases with a focus on individual-level outcomes and assessing strategies such as travel restrictions, quarantine without testing, social distancing, and on-arrival PCR testing. After the development of diagnostic tests and vaccines, modeling studies projected population-level outcomes and investigated these tools to limit COVID-19 spread. Very few published studies included rapid antigen screening strategies, costs, explicit model calibration, or critical evaluation of the modeling approaches.

Conclusion: Future modeling analyses should leverage open-source data, improve the transparency of modeling methods, incorporate newly available prevention, diagnostics, and treatments, and include costs and cost-effectiveness so that modeling analyses can be informative to address future SARS-CoV-2 variants of concern and other emerging infectious diseases (e.g., mpox and Ebola) for travel-related health policies.

1. Introduction

Early in the COVID-19 pandemic, most countries implemented recommendations and regulations to reduce the importation of SARS-CoV-2 via travel, including travel bans, quarantine, isolation, pre/post travel testing, and combinations of these strategies [1,2]. Although these regulations might have assisted in limiting transmission during the initial spread of SARS-CoV-2, the impact of travel-related containment strategies likely diminished as the virus became more widespread [3]. On June 12, 2022, the US Centers for Disease Control and Prevention (CDC) lifted the requirement for a negative COVID-19 test to enter the United States from a foreign country (which had initially been issued on January 12, 2021), as well as removing the requirements for mask-wearing during public travel [4]. These decisions echoed a global

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relaxation of travel regulations [5]. However, substantial questions remain regarding travel-related COVID-19 policies given the ongoing emergence of new variants of concern, uncertainty regarding the durability of protection from vaccination, and the availability of new diagnostic and treatment options [6].

Modeling is a methodology that can be used to investigate both the clinical impact and cost-effectiveness of different clinical and public health strategies [7–9]. Models incorporate available data and current biological understanding and can be used to examine specific strategies focused on explicitly defined outcomes. Comparing different modeling approaches thematically and technically can highlight areas where modeling enhancement and additional data are needed, as well as where specific strategies should be examined. Gaps in data can be identified to focus research attention on topics and questions that can affect policy [10].

The objective of this scoping review was to identify, compare, and evaluate published modeling analyses regarding approaches to reduce SARS-CoV-2 transmission during travel as the pandemic evolved from early 2020 through mid-2022. Using a systematic approach, we critically assessed modeling methods, travel-related strategies to reduce COVID-19 cases, and model-projected outcomes among the published analyses [9]. We identified areas of focus for future modeling approaches to guide policy regarding travel-related strategies for diseases, including COVID-19 and other emerging infectious diseases.

2. Methods

2.1. Search strategy

We used free text terms to search for articles written in English and indexed in PubMed, which includes MEDLINE indexed journals and journals/manuscripts deposited in PMC [11], from December 2019 through September 2022. The search terms "testing," "isolation," or "quarantine" were each paired with "COVID," or "SARS-CoV-2," "travel, " and "modeling." We searched articles by using three different combinations of search terms separately, combined the search results, and created a results database.

2.2. Inclusion/exclusion criteria

After removing duplicate studies, we screened articles based on the titles and abstracts using the following criteria: 1) the title or abstract included the term, "model(s/ing); " 2) the study's main focus was COVID-19; 3) the study assessed public health strategies to contain COVID-19 at a destination after travel (i.e., not only projecting SARS-CoV-2 natural history or epidemiology); 4) travel was not daily commuting or mobility. We excluded studies if they were not primary research (e.g., book chapter, review, or case study/series). We assessed the full text of all articles that met the inclusion criteria.

2.3. Data extraction, synthesis, and critical review of modeling studies

Two reviewers (SK, EG, or EPH) independently extracted the following data from the selected articles: (1) study objective, (2) method of modeling and program used, (3) outcomes evaluated (e.g., the number of secondary transmissions from travelers, the risk of an outbreak in the destination country), (4) setting (e.g., country, transportation for travel), (5) strategies examined (e.g., testing, quarantine), (6) cost estimation, and (7) simulated population characteristics (e.g., vaccination coverage, adherence to testing policy). Next, the two reviewers systematically examined the 43 selected articles using 26 pre-specified criteria to evaluate the quality and rigor of modeling analyses in four domains: model development, model testing, model analysis, and "other" qualifications [9]. A detailed methodology of this critical evaluation was previously published [9]. We compared and summarized the extracted data and evaluations directly; discrepancies were resolved by discussion or adjudicated by a third, senior reviewer (EPH).

3. Results

3.1. Search results

We identified 720 articles from PubMed that fit our search criteria, of which 207 were duplicates (Fig. 1). We assessed the titles and abstracts of the remaining 513 articles, excluding 349 articles and selecting 164 articles for a detailed review of the abstract, from which we excluded 97 articles based on the eligibility criteria. We then reviewed the full text of the remaining 67 articles and excluded 29 for the following reasons: (1) focused on daily commuting or mobility (n = 26) and (2) did not assess the impact of travel-related strategies on the population at the destination (n = 3). We added five additional articles that were not initially captured in our search strategy based on author recommendations and bibliographies from the previously selected 38 papers. Table 1 summarizes the 43 included articles with summarized extracted data and critical evaluation.

3.2. Model structure

The most common type of model was compartmental, although the authors referred to this type of model using different terms. Most studies used extended susceptible-infected-recovered (SIR) (n = 6) [1,15,24,28,35,37] or susceptible-exposed-infected-recovered (SEIR) models (n = 15) [16–18,21,26,27,29,33,36,37,40–42,44,49] to account for COVID-19 transmission. One model added a compartment, "L," for infected individuals in the latent stage and a compartment, "A," for undetected, infectious individuals [1]. In another model, a distinct compartment, "P," was included for the presymptomatic state, and the infected state (I) was divided into subcompartments, asymptomatic (I_a) and symptomatic (I_s) [42]. Authors used the term "mathematical framework/model(s)" most frequently (n = 5) when describing the modeling approach, regardless of the model type [20,23,25,32,47]. All analyses specified a time horizon to assess the outcome measures pertinent to time from a specific point (e.g., departure and arrival). Studies that focused on a congregate setting or a setting with zero COVID-19 cases at the model start more often used an individual-level model (e.g., multi-agent model, microsimulation model) to evaluate the implications of one newly infected individual [22,36,44–46].

3.3. Model outcomes

We categorized model outcomes as (1) individual travelers and (2) population-level outcomes. Individual-level outcomes capture the short-term implications of strategies and the potential burden on transportation authorities and border control at the destination, including the number of infectious travelers detected on the day of travel [7,16,19,46], the number of imported cases [12,14,18,21,23,28,34,42], and the ratio of detected, infected individuals on arrival compared with all infected passengers [3,38]. Population-level outcomes capture the longer-term effects of strategies and burden on the destination's local jurisdictions and healthcare facilities [14], including the possibility of an outbreak at the destination [1,28,33] and the number of days during which travelers would remain infectious after the end of quarantine [2,7]. Based on these categorizations, 12 studies focused on individual traveler outcomes[16,19,22,23,27,33,34,36,41,42,46,49], 19 studies included population-level outcomes [2,8,20,25,26,29–33,37–40,43–45,47,48], and 12 studies projected both types of outcomes [1,3,7,12–15,17,18,21,28,35,36].

3.4. Software program

Of the 43 studies, 23 stated the software package or programming language used. Those studies used R (n = 10) [1,2,7,16,19–21,25,40,

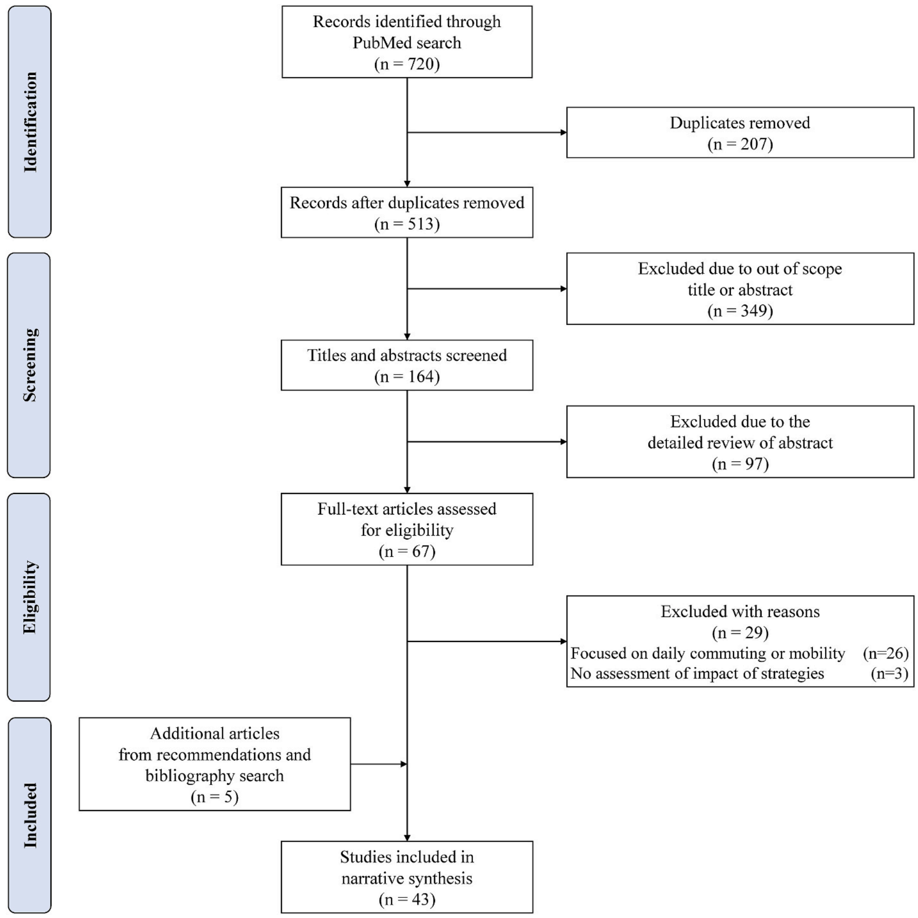

Fig. 1. Flow chart of the study selection. This figure summarizes the search and selection process for the selected 43 modeling articles. We first identified 720 articles from PubMed. After removing 207 duplications, we assessed the titles and abstracts of the remaining 513 articles and excluded 349 articles based on the inclusion criteria (1) the title or abstract included the term, "model(s/ing)". We closely reviewed the abstracts of the remaining 164 articles and excluded 97 articles based on the inclusion/exclusion criteria. Next, we reviewed the full text of the remaining 67 articles and excluded 29 articles with reasons. We selected 43 articles for inclusion with additional five articles based on recommendations and review of the bibliographies of the other articles.

48], MATLAB (n = 6) [28–30,32,47,49], Python (n = 5) [3,8,17,35,38], C++ (n = 1) [31], or Pascal (n = 1) [33]. The remaining 20 studies did not explicitly state the software package used to perform the modeling [12–15,18,22–24,26,27,34,36,37,39,41–46].

3.5. Settings

3.5.1. Geographic location

Fifteen of the 43 studies did not specify the geographical location in which the models were set [1,3,8,14,19,20,23–25,31,32,35,37,38,42]. Nineteen papers considered unique countries or settings for the models: mainland China (n = 8) [12,15,16,29,36,44,48,49], the United States (n = 2) [7,43], New Zealand (n = 2) [33,45], Hong Kong (n = 2) [28,34], Canada (n = 1) [29], India (n = 1) [18], Saudi Arabia (n = 1) [39], South Africa (n = 1) [40], and Vanuatu (n = 1) [46]. Multiple locations of origins or destinations were considered by seven papers: mainland China and Singapore (n = 1) [21], regions of the United States, the United Kingdom, and European countries together (n = 1) [2], mainland China and Hong Kong (n = 1) [27], the Isle of Man and Israel (n = 1) [30], Australia and mainland China (n = 1) [13], mainland China, Italy, and the Republic of Korea (n = 1) [26], and all 26 European Union countries (n = 1) [47]. Two studies considered a cruise ship setting without specifics regarding geographical location [22,41].

3.5.2. Type of travel

The 43 selected papers included international travel only (n = 23) [1–3,13,14,20-23,25,26,28,31,33–35,37,38,40,42,45–47], domestic travel only (n = 8) [7,15,16,29,36,43,44,49], both international and domestic travel (n = 5) [12,18,29,39,48], or did not explicitly state the type of travel (n = 7) [8,19,24,27,30,32,41]. Most studies were explicit regarding the type of transportation: air (n = 18) [2,3,7,12–14,18,23,25,29,33–35,37,38,40,42,45], train (n = 2) [36,49], both air and train (n = 1) [15], or cruise ship (n = 2) [22,41]. Twenty papers applied modeling to unspecified types of transportation [1,8,16,19–21,24,26–32,39,43,44,46–48]. Among them, two studies considered land border crossing [31,40]. Most papers assessed one-way travel, with only two studies including round-trip travel [47,49].

3.6. Strategies

Published modeling studies focused on the impact of strategies to limit COVID-19 among travelers, including pre-travel screening, quarantine and isolation, screening with a range of diagnostic tests on or after arrival, and a combination of these strategies.

3.6.1. Pre-travel screening

We defined pre-travel screening as diagnostic tests and symptom screening conducted before or at departure. Of the 18 papers that evaluated pre-travel screening, 14 papers focused on testing before or at the time of departure [3,7,22,23,25,33,37,38,40–42,44–46], two papers focused only on symptom screening at departure [27,34], and two papers included both testing and symptom screening [2,36]. Of the 16

Table 1
Summary of included studies.

Author(s), year	Location	Strategy					Costs	Summary of results
		Pre-travel screening	Quarantine	Isolation	Testing			
					PCR	Ag		
Arino et al., 2020 [1]	NS	–	✓	–	–	–	✓	- The rate of importations is more critical in determining the risk of local transmission than the use of NPIs locally. The latter influences the severity of the outbreaks. - Quarantine after arrival is an efficacious way to reduce the rate of importations.
Chinazzi et al., 2020 [12]	Mainland China	–	–	–	–	–	–	- Travel quarantine from Wuhan would have delayed the epidemic by only 3–5 days in Mainland China but would have a stronger effect at the global scale. Global case importations would have decreased by about 80 % until mid-February 2020. - Keeping 90 % of travel bans to and from Mainland China would have a modest impact on the transmission without combining with a 50+% reduced transmission in the community.
Costantino et al., 2020 [13]	Australia from Mainland China	–	✓	✓	–	–	✓	- The modeled impact without a travel ban would result in 2000+ cases and 400 deaths, with the epidemic locally remaining in China and no importations from other countries. The full travel ban would have reduced cases by about 86 %, while a partially lifted travel ban would have a minimal impact and may be a policy option.
Dickens et al., 2020 [14]	NS	–	✓	✓	✓	–	✓	- The average reduction in case importations across countries compared to S1 (No screening) would be 90.2 % for S2 (Screening of all travelers on arrival and 7-day isolation for test-positive, with release into the community only with a negative test), 91.7 % for S3 (Screening with 14-day isolation of test-positives followed by a negative test), 55.4 % for S4 (No screening but a 7-day mandatory quarantine for all), 91.2 % for S5 (No screening but 14 days of quarantine) and 77.2 % for S6 (Screening of all and entry prohibited for test-positives).
Hossain et al., 2020 [15]	Mainland China	–	–	✓	–	–	–	- The border control that decreased 90 % of the passengers would have resulted in an additional 32.5 days of outbreak arrival time. With the medium the basic reproduction number (R_0) (1.68), the border control would have had a weaker effect, with an additional 20.0 days of outbreak arrival time under the same control level. With the high R_0 (2.92), the effect on curbing the outbreak risk would have been very low, with only an additional 10 days. - With the low R_0 (1.4), quarantining an individual in one day after the person had become infectious would have gained an additional 44.0 days of outbreak arrival time. With the medium R_0 (1.68), the quarantine would have had a half effect on the gained time (24.1 days), compared with the low R_0 scenario with the same quarantine duration. With the high R_0 (2.92), only 10.0 days would have been gained.
Lai et al., 2020 [16]	Mainland China	–	–	✓	–	–	✓	- Lifting travel bans on February 17, 2020, would not lead to a case increase across China if social distancing could be maintained, even at a limited level of 25 % contact reduction through late April. - If interventions in China could have been conducted one week, two weeks, or three weeks earlier, cases could have been reduced by 66 % (IQR 50–82 %), 86 % (81–90 %), or 95 % (93–97 %), respectively.
Linka et al., 2020 [17]	Canada	–	✓	–	–	–	–	- When fully reopening the border, one new case would enter the province every other day. Under the current conditions, restricting airline travel from abroad to Canada is more effective than fully reopening and quarantining 95 % of the incoming individuals.
Mandal et al., 2020 [18]	India	–	–	✓	NS	NS	–	- Quarantining symptomatic individuals would identify and quarantine 50 % of infections within three days of developing symptoms. - If R_0 is 1.5 and asymptomatic infections are not infectious, screening would reduce the cumulative incidence by 62 %. If R_0 is 4.0, and asymptomatic infections are half as infectious as symptomatic, this projected impact falls to 2 %.
Arino et al., 2021 [19]	NS	–	✓	–	–	–	✓	- The effect of importations would be marginal compared with community-based transmission once an imported variant is circulating in the community. - Quarantine would be efficacious in reducing case importation rates, while travel bans would potentially delay transmissions after importations only if implemented immediately after the variant emerged.

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Table 1 (*continued*)

Author(s), year	Location	Strategy					Costs	Summary of results
		Pre-travel screening	Quarantine	Isolation	Testing			
					PCR	Ag		
Ashcroft et al., 2021 [20]	NS	–	✓	✓	✓	✓	✓	- Shortening quarantine durations from ten to seven days would not increase the transmission risk, if paired with PCR testing on day five (with people testing positive being confined for longer). - The quarantine could be reduced to six days if rapid antigen tests were used.
Bays et al., 2021 [3]	NS	✓	–	–	NS	NS	–	- A one-time screening on arrival would not be sufficient to reduce travelers with infections entering a destination country.
Chen et al., 2021 [21]	Mainland China (excluding Hubei province) and SGP	–	✓	✓	–	–	–	- When reducing 30 % of traveler arrivals, the total infected cases would be 88.4 (IQR 87.5–89.6) and 58.8 (IQR 58.3–59.5) times more than those when reducing 99 % of arrivals in mainland China and SGP respectively. - If the global daily new infections reached 100,000, 85 %–91 % of inbound travelers would be stopped to keep the daily new infections below 100 for a country with a similar travel volume to SGP.
Chowell et al., 2021 [22]	Diamond Princess Cruise ship	✓	–	✓	✓	–	✓	- PCR testing at departure and daily testing of all aboard, with increased social distancing and other measures, would allow for rapid detection and isolation of infections and dramatically reduce the likelihood of COVID-19 transmissions.
Clifford et al., 2021 [2]	UK from US and EU	✓	✓	–	✓	–	✓	- An 8-day quarantine with a PCR testing on day 7 could reduce infection importations into the community by 94 % compared with a scenario without quarantine and testing.
Dickens et al., 2021 [23]	NS	✓	✓	–	✓	✓	✓	- With a 14-day quarantine, 2.2 % (range: 0.5–8.2 %) of imported infections would be missed on average. - Entry + exit testing would result in 3.9 % (3.1–4.9 %) of imported cases being missed with 7-day quarantine (0.4 % [0.3–0.7 %] with 21-day quarantine). Daily testing would be the most risk-averse strategy and would further reduce the proportion to 2.5–4.2 % at day 7 and 0.1–0.2 % at day 21.
Hu et al., 2021 [24]	NS	–	✓	–	NS	NS	✓	- The pandemic control policy would have a more significant effect in the initial stages of the pandemic when the proportion of infected people was low. - With the risk caused by the population arriving from region A, the optimal response of region B is to put more people in lockdown. This policy would be effective in preventing more infections but cause more economic losses.
Johansson et al., 2021 [25]	NS	✓	✓	✓	✓	✓	✓	- A 14-day quarantine after arrival without symptom monitoring or testing would decrease post-travel transmission by 96–100 %. - A 7-day quarantine after arrival with symptom monitoring and testing on day 5–6 would also be effective (97–100 %) in reducing travel-related transmissions compared with no intervention and less burdensome, which may increase adherence.
Kabir et al., 2021 [26]	Mainland China, Italy & the Republic of Korea	–	✓	✓	–	–	✓	- Unless functioning ideally, partial travel bans allowing for equal or more than one traveler's arrival would be ineffective in curbing an outbreak. - Funds spent could reduce the numbers of infections and improve quarantine policy success.
Kiang et al., 2021 [7]	US	✓	✓	–	✓	✓	✓	- Pre-travel PCR testing would reduce the number of infectious days from 8357 to 5401 (3917–8677), a 36 % (29–41) reduction, and identify 569 (88 % [76–92 %]) of 649 actively infectious travelers on the flight date. - Adding post-travel quarantine and PCR would reduce the number of infectious days to 1474 (1087–2342), an 82 % (80–84 %) reduction, compared with the base case.
Kwok et al., 2021 [27]	HK and mainland China	✓	✓	–	–	–	–	- With an R_0 of 2.2, a reduction in daily travelers from 200,000 to 0 from February 8, 2020, would reduce the cumulative COVID-19 infections in HK by 13.99 % (from 29,000 to 25,000). - Keeping complete border closure and implementing public health measures to maintain the effective reproduction number (Rt) below 1.6 would be required, to prevent the facilities in HK from being overwhelmed.
Leung et al., 2021 [28]	HK	–	✓	✓	✓	–	✓	- At vaccine efficacy of 0.80 (reducing susceptibility to infection), 0.50 (reducing SARS-CoV-2 infectivity), and 0.95 (reducing symptomatic cases), vaccination coverage would have to be 100 % for people 30y or older to avoid an outbreak when relaxing public health and social measures, which would overload the local health-care system, with an assumed pre-vaccination effective reproduction number (Re) of 2.5. - Testing and quarantine of 5 or more days would have to be maintained for inbound travelers to minimize the local outbreak reintroduction risk until high vaccination coverages are attained locally and globally in most countries.

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Table 1 (*continued*)

Author(s), year	Location	Strategy					Costs	Summary of results
		Pre-travel screening	Quarantine	Isolation	Testing			
					PCR	Ag		
Lin and Peng, 2021 [29]	Mainland China	–	✓	✓	NS	NS	–	- The significant increase in the detection rate of infectious cases because of the testing efficiency expansion, would have been as effective as city lockdowns, as the reduction in new infections up to mid-March 2020 was seen. However, in an extended analysis to July 2020, increasing the detection rate to at least 50 % would be the only reliable way to control the disease spread. - City lockdowns would be effective intervention in the short term but effective testing, detection, and quarantine measures are important in containing the disease spread in the long term.
Peng et al., 2021 [8]	NS	–	✓	✓	✓	✓	✓	- One PCR test before the end of quarantine could decrease quarantine duration to 10 days. Two tests could decrease the duration to 8 days, and three highly sensitive tests could decrease the duration to 6 days.
Sachak-Patwa et al., 2021 [30]	the Isle of Man (a British crown dependency in the Irish Sea) and Israel	–	–	–	–	–	–	- The outbreak risk would not completely be removed when travel bans and other NPIs are lifted even once vaccine programs are completed. - When travel bans are lifted, implementing surveillance of incoming travelers to detect infections would be necessary.
van der Toorn et al., 2021 [31]	NS	–	✓	✓	✓	✓	–	- Testing on day 4 (PCR) or 5 (Ag) during quarantine would be as efficient as a 10-day quarantine for incoming travelers. Testing on day 8 (PCR) or 10 (Ag) days during quarantine would be as efficient as a 14-day post-exposure quarantine. - Exit from isolation of infected individuals 13 days after symptom onset may reduce the transmission risk to <0.2 %.
Wells et al., 2021 [32]	NS	–	✓	✓	✓	–	✓	- Testing on exit (or entry and exit) of quarantine could reduce the 14-day quarantine duration by 50 %, while testing on entry would shorten the duration by at most one day.
Wilson et al., 2021 [33]	NZ	✓	✓	✓	✓	–	✓	- Historical flight data suggested a median time to an outbreak of 0.2 years (3 days–1.1 years) or a mean of 110 flights per outbreak. However, the combined use of a pre-departure saliva PCR, three PCR tests (on days 1, 3 and 12 after arrival), and other interventions (mask-wearing and contact tracing) could reduce the outbreak risk after a median of 1.5 years (20 days–8.1 years).
Yang et al., 2021 [34]	HK	✓	✓	–	✓	–	–	- With 14-day quarantine and testing on day 12, the Philippines would have caused the greatest importation risk among the studied countries/regions (95.8 % of releasing at least one infectious traveler, 95 % credible interval, 94.8–96.6 %). - Relaxing quarantine to 7 days with a second PCR on day 5 for travelers from low prevalence countries or regions would not cause greater importation risks than applying strict control measures to travelers from high prevalence areas.
Zhong, 2021 [35]	NS	–	✓	✓	NS	NS	✓	- Social distancing policies and some degree of travel bans should have higher priority. - Extending the quarantine duration could compensate for the lack of testing.
Zhou et al., 2021 [36]	Mainland China	✓	–	✓	✓	–	✓	- Pre-travel testing could reduce the number of infections. - Compared with no testing, testing travelers from risk tier 2–4 regions 3 days before travel could significantly reduce the transmission risk.
Zhu et al., 2021 [37]	NS	✓	✓	–	✓	✓	✓	- Strict border control in regions where local disease spread is eliminated (e.g., China), is justifiable. However, such a measure is not necessary for other places. Regions successfully confining the virus by internal measures could open up to similar regions without additional border controls as long as the imported risk does not increase. - The effectiveness of border closures would depend on the local containment measures. Contact tracing with isolation would be an effective way to reduce the reproduction rate, but further local restrictions would still be needed.
Bays et al., 2022 [38]	NS	✓	✓	–	NS	NS	✓	- Testing after a 2-day isolation period could detect up to 41 % of infections. - Longer self-isolation would raise detection rates. An 8-day self-isolation would result in detection rates of up to 94 % for infected travelers.
Bisanzio et al., 2022 [39]	Saudi Arabia	–	✓	–	–	–	–	- Lifting the travel ban without quarantine could greatly increase infection cases, hospitalizations, and deaths, resulting in 3,062,395 infections, 398,111 hospitalizations, and 49,611 deaths in estimation. - Quarantine requirements could have reduced cases, hospitalizations, and deaths by 87 % with a quarantine adherence of 50 %, and by 88.5 % with adherence of 80 %.

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Table 1 (*continued*)

Author(s), year	Location	Strategy					Costs	Summary of results
		Pre-travel screening	Quarantine	Isolation	Testing			
					PCR	Ag		
Chevalier et al., 2022 [40]	South Africa	✓	–	–	–	✓	✓	- With a high volume of international arrivals/high COVID-19 prevalence, Ag testing would not be efficient enough to prevent the infection spread within a community, when prevalence in the destination country and Rt are low.
Guagliardo et al., 2022 [41]	Cruise Ship	✓	–	✓	✓	–	–	- 7-day voyages would reduce infections by 70 % compared to 14-day voyages. On 7-day voyages, the most effective interventions would be reducing the number of individuals onboard (43.3 % reduction in infections) and testing travelers and crew (42.0 % reduction). All four interventions would reduce transmissions by 80.1 %, but no single intervention or combination would eliminate transmissions.
Kamo et al., 2022 [42]	NS	✓	✓	✓	NS	NS	✓	- One test on the day before departure would be the most effective in reducing the density of infected travelers. - Isolation with one test on day 7 or 8 after arrival would be comparable with 11- or 14-day isolation without other measures, respectively.
Shah et al., 2022 [43]	US	–	✓	✓	–	–	–	- Without any mitigation measures, infectious and hospitalized people would increase. - When interstate and international travel was restricted and the population was placed under quarantine, the probability of exposure and infection would decrease significantly; the recovery rate would increase substantially.
Shen et al., 2022 [44]	Mainland China	✓	–	✓	✓	–	✓	- For travelers from medium-high risk areas, pre-travel PCR within 3 days could limit the number of infected individuals in Yangzhou to 50. - If the population density of the chess and card room dropped by 40 %, the number of infected individuals would decrease by 54 people within 7 days.
Steyn et al., 2022 [45]	NZ	✓	✓	✓	✓	✓	–	- Home isolation would have a significantly higher risk than the current mandatory 14-day isolation in government-managed facilities. - Combinations of testing and home isolation could reduce the community outbreak risk to one outbreak per 100 infected travelers.
van Gemert et al., 2022 [46]	Vanuatu	✓	–	–	NS	NS	–	- The number of infectious individuals in the community would decrease by 98–99 % when travel is restricted to those from low-prevalence countries, compared with no restrictions on the country of departure. - The number would decrease further, by 61–63 % for each testing strategy, when travel is restricted to vaccinated travelers only.
Wells et al., 2022 [47]	26 EU countries	–	✓	✓	✓	✓	✓	- Quarantining for 3 days or shorter period with RT-PCR or Ag testing at the end of the quarantine would be sufficient.
Wong et al., 2022 [48]	Mainland China	–	✓	✓	✓	–	✓	- To avoid new infections, quarantining all attendees before the event would be the most effective, followed by quarantining all international attendees, testing all other attendees, and testing all attendees before the event and on day 7. The testing strategy would be influenced by the prevalence outside the event province.
Zou et al., 2022 [49]	Mainland China	–	✓	✓	–	–	–	- At least 61.38 % of individuals would need to be vaccinated to achieve herd immunity. - When vaccination and quarantine are implemented simultaneously, it would be necessary to ensure that the quarantine rate satisfies p2 (quarantine ratio) > 38.74 % for preventing the disease spread.

Note: This table summarizes the results of extracted data for the 43 articles assessed in this review. This table flags the existence of the items of strategies and costs, with marks signifying considered, considered but not specified, or not considered.
Abbreviations: PCR = polymerase chain reaction test; Ag = Antigen test; ✓ = Considered; (–) = Not considered; NS = Considered, but not specified; NPI = Non-Pharmaceutical Interventions; UK = the United Kingdom; EU = Europe; SGP = Singapore; HK = Hong Kong; NZ = New Zealand.
Definition: Pre-travel screening = diagnostic tests and symptom screening conducted before or on departure.

papers that investigated pre-travel testing, 10 papers included testing only before departure (e.g., testing a few days before the flight) [2,7,25,33,36,37,40,42,44,45], three papers included testing only at the time of departure (e.g., testing at the airport immediately before boarding) [22,23,41]. The other three papers included pre-travel testing, but the timing of testing was not clearly stated [3,38,46]. Most papers considering testing before departure examined the implications of testing between 7 days and 1 day before departure; only two papers assessed a pre-travel testing strategy in which testing occurred 9 days [44] or 14 days [36] before travel. All four articles that included a symptom screening strategy situated the screening at the time of departure with a range of impact (i.e., percentage of symptomatic individuals prevented from traveling): 70 % [2,34], 99 % [27], or 100 % [36] that were mostly assumptions [2,27,36]. Only one analysis provided data that 70 % were prevented from traveling given symptom screening [34].

3.6.2. Quarantine and isolation

Quarantine is a public health strategy that restricts the movement of individuals exposed to a pathogen to identify whether infection occurs and to prevent transmission before infection is confirmed; isolation is a strategy that separates individuals infected with a disease from others [50]. Based on these definitions, 38 studies investigated quarantine or isolation: quarantine strategies only (n = 12) [1,2,7,17,19,23,24,27,34,37–39], isolation strategies only (n = 7) [15,16,18,22,35,41,44], or both quarantine and isolation (n = 19) [8,13,14,20,21,25,26,28,29,31–33,35,42,43,45,47–49].

Of the 31 studies that evaluated quarantine strategies, 24 were focused on travel-related quarantine [1,2,7,14,17,19,20,21,23,25,28,31–35,37–39,42,45,47–49] and seven on quarantine that was not related to travel [8,13,24,26,27,29,43]. Of the 24 studies dealing with travel-related quarantine, 21 studies included comparing strategies in which all travelers were quarantined versus no travelers quarantined [1,2,7,14,19–21,23,25,28,31–35,38,39,42,45,47,48]. Three studies compared quarantining different percentages of travelers [17,37,49]. Of the seven studies using non-travel-related quarantine, five studies used quarantine for individuals exposed to or in close contact with infected individuals [8,13,26,27,43], one study used quarantine for the entire destination community [24], one study used quarantine for the tested individuals waiting for the results confirmation [29]. Most studies varied the duration of quarantine to determine the optimal quarantine strategy based on the study objectives. The maximum evaluated duration of quarantine was 10 days (n = 1) [20], 14 days (n = 19) [2,7,8,13,14,17,19,21,25,28,31,32,37,38,42,45,47–49], 21 days (n = 3) [23,33,34], and longer than 25 days (n = 3) [1,24,35]. The other five studies did not specify the quarantine length [26,27,29,39,43]. Only three studies explicitly differentiated home-based quarantine from facility-based quarantine [24,37,45].

Isolation was considered in 26 papers, initiated by either symptom onset or a positive test result. Isolation was applied to only symptomatic or test-positive travelers (n = 18) [8,14,16,20–22,25,32,33,35,36,41–43,45,47–49] or anyone, including travelers who are symptomatic or test-positive in the study population (n = 5) [13,15,18,31,44]. Nineteen papers used isolation as a distinct strategy [14–16,18,21,25,26,31–33,35,36,43,45,47,49], whereas two papers accounted for people in quarantine transitioning to isolation after a positive test result or symptom onset [8,20]. Eight papers included isolation in the modeled setting but did not examine its influence as a unique strategy [13,22,28,29,41,42,44,48]. When isolation was used as a distinct strategy or combined with quarantine, eight papers assumed an isolation duration of up to 14 days and evaluated secondary transmission risks with shortened durations [8,14–16,21,31,45,49].

3.6.3. Test characteristics and performance

Diagnostic tests included polymerase chain reaction (PCR) tests and antigen tests. PCR tests usually provide more reliable results but with a longer turnaround time. Antigen tests are point-of-care tests that have lower sensitivity and specificity but provide results with shorter time (within 1 h) [51]. Twenty-nine analyses included testing as a strategy: PCR only (n = 11) [2,14,22,28,32,33–35,41,44,48], PCR and antigen tests (n = 10) [7,8,20,23,25,31,37,40,45,47], and an unspecified type of testing (n = 8) [3,18,24,29,35,38,42,46]. No analysis assessed the use of antigen tests only. One study projected the potential benefits of using antigen tests on arrival for incoming international travelers who had already received negative PCR test results at departure [40].

Regarding input parameter estimates, seven of the ten analyses that included both PCR and antigen tests incorporated a higher sensitivity for PCR than for antigen tests [7,8,23,31,40,45,47]; three analyses examined the implications if the model was parameterized with the same or higher sensitivity for antigen tests compared with PCR tests [25,37]. Parameter estimates for test sensitivity were often varied according to the time since infection (n = 16) [2,7,8,14,22,23,25,28,31–34,36,45–47] and were associated with the viral load distribution and symptoms (symptomatic or asymptomatic) (n = 3) [8,34,46]. Estimated turnaround time of test results was parameterized in ten analyses (PCR: 0 and 2 days; antigen tests: within hours) [2,7,8,20,22,23,25,32,36,47]. The other 19 analyses did not include an explicit input parameter for test turnaround time [3,14,18,24,28,29,31,33–35,37,38,40–42,44–46,48].

3.6.4. Testing strategies

In the 29 studies that assessed specific testing strategies, testing was incorporated as (1) surveillance at the population level (n = 4) [22,24,29,41], (2) detection of infection after high-risk activities (e.g., close contact with infected individuals) (n = 1) [36], (3) border control measures at departure or the destination (e.g., pre-travel and on-arrival test) (n = 7) [3,18,33,37,40,44,48], or (4) an after-arrival measure to determine quarantine necessity and lengths (e.g., negative test for travelers to end quarantine) (n = 17) [2,7,8,14,20,23,25,28,31,32,34,35,38,42,45–47]. When testing was used as surveillance at the population level, the simulated population was randomly tested at defined time points [22,24,29,41]. When a study tested the population after high-risk activities, individuals could freely move around and were tested at a defined time after the activity [36]. A pre-travel or an on-arrival test was used to estimate the number of infections at a specific site (e.g., borders) [3,18,33,37,40,44,48]. In some analyses, after-arrival tests were conducted to determine whether the individual could end quarantine or isolation [2,7,8,14,20,23,25,28,31,32,34,42,45,47]; in other analyses, after-arrival testing without quarantine was used as a distinct strategy compared with mandatory quarantine (without testing) [7,25,35,45,46].

In the 17 articles that defined screening as a testing strategy accompanied by quarantine and isolation, screening was most frequently performed either at the end of quarantine or 2 days before the final day of the quarantine, assuming that the PCR result becomes available after 2 days (n = 11) [2,7,8,14,23,28,32,34,45,47]. Additional screening strategies included: 0–3 days before the end of quarantine (n = 1) [20], 3 days before the end of quarantine (n = 1) [42], 0–10 days after the start of quarantine (n = 1) [31], daily until day 7 post-exposure (n = 1) [25], or no specified timing (n = 2) [35,38]. Testing frequencies included once (e.g., only at the end of quarantine), twice (e.g., at the start and the end of quarantine), and/or daily. This type of testing strategy was usually compared with other screening and quarantine strategies to determine the most effective strategy, defined as the lowest transmissibility (e.g., the fewest numbers of infectious individuals released from quarantine) or detected infections (e.g., a probability that a case that is initially unobservable becomes observable).

3.6.5. Other strategies

Several studies examined additional strategies with different policy targets and country-specific infection control measures. Eight studies assessed the impact of border restrictions on imported infections from international travelers [12–15,17,21,26,29], with seven studies using real flight or mobility data to parameterize the number of travelers

[12–15,17,21,29]. Six studies examined the impact of social distancing and mask-wearing on virus transmission [8,16,22,33,35,39]. Six articles incorporated vaccinated populations into the models [28,30,45–49], of which three studies evaluated the implications of COVID-19 vaccination requirements for travelers or vaccination coverage of the destination community to reduce viral transmission [28,30,46].

3.7. Costs

Of the 43 studies in this review, only four studies explicitly assessed costs borne by the government or society [24,26,35,36] (see Section 3.10.) Seventeen articles did not discuss costs at all [3,12,15,17,18,21,27,29–31,34,39,41,43,45,46,49], and 22 studies made brief comments regarding either testing costs or the need for the inclusion of economic and government costs [1,2,7,8,13,14,16,19,20,22,23,25,28,32,33,37,38,40,42,44,47,48].

3.8. Additional parameters

Some models incorporated additional parameters to simulate situations about viral characteristics, human behaviors, demographics, and transmission during transit.

Three studies examined the implications of SARS-CoV-2 variants of concern and reinfection. One study included an assessment of variants that were prevalent in the study settings (Delta G/478K.V1 and Omicron B.1.1.529+BA) [47]. One study examined the infection dynamics in a hypothetical scenario with two variants of concern in three settings—a closed community, a community importing the variants, and transmission from an exporting location to an importing location [19]. The other study used the estimated transmissibility of Alpha B.1.1.7 and Delta B.1.617.2 [28]. Only one study incorporated COVID-19 reinfection to recovered individuals in the model with different levels of past immunity [35].

Most studies assumed 100 % adherence to public health policies, such as self-isolation and travel restrictions for symptomatic individuals (n = 31) [1,3,8,12–16,18,19,21–24,27–32,35–38,40,42–44,46,48,49]. While some studies explicitly mentioned the assumption of 100 % adherence, others outlined no parameter regarding adherence, therefore assuming 100 % adherence. Some publications varied the level of adherence in sensitivity analysis (range, 0–100 %) (n = 8) [7,17,20,25,26,39,41,47]. In one study, a substantial number of European countries would select travel bans over required quarantine periods, when adherence to quarantine policy declined from 100 % to 25 %, based on the model-projected number of increased infections [47].

Age-specific characteristics were incorporated in only four analyses, of which all considered age-specific vaccination coverage [28,44,45,47]. Other age-specific characteristics included were susceptibility to the pathogen (n = 2) [28,45], clinical presentation (n = 2) [28,45], and vaccination effectiveness (n = 1) [47].

Six articles focused on or included transmission that occurs during transit [22,33,37,41,42,49], of which three analyses incorporated in-flight transmission [33,37,42]. Two analyses examined the effectiveness of screening and non-pharmacological interventions during ocean cruises [22,41], and another combined an SEI model in transit with an SEIR model in origin and destination provinces [49].

3.9. Critical review of the reviewed articles

Table 2 presents the results of the critical evaluation by 26 pre-specified criteria for each study. The scores range from nine to 22 with an average of 15.2. Only two studies obtained scores below 11 (n = 2) [12,43]; another two studies had scores greater than 20 (n = 2) [30,48]. Studies with high total scores from the critical evaluation did not always meet criteria in the modeling testing domain.

Fig. 2 summarizes the critical evaluation stratified by 26 criteria. Several criteria were met in most studies. The majority of the articles reported an explicit modeling objective (n = 42) [1–3,7,8,12–25,27–49], quantitative results (n = 42) [1–3,7,8,12–25,27–49], sensitivity analyses of the input parameters (n = 41) [1–3,7,8,12,13,15–42,44–49], problem definition (n = 40) [1–3,7,13–17,19–49], discussion about strategies and policies (n = 39) [1,2,7,8,14–39,41–49], model conceptualization (n = 39) [1–3,7,13–17,19–32,34–49], sources of funding (n = 38) [1,2,7,8,12–20,22–36,39–41,43–49], and conflicts of interest (n = 38) [1,2,7,8,12–36,39–42,44,45,47–49].

Several essential criteria for reproducibility and generalizability were not met in a large portion of studies. For instance, only half of the studies addressed the criteria of software used (n = 24) [1–3,7,8,16,17,19–21,25,28–33,35,38,40,44,47–49], modeling code availability (n = 18) [1–3,7,8,16,20,21,25,29–33,35,38,40,47], and discussions of reproducibility (n = 16) [1–3,7,8,16,20,21,29–32,35,38,40,47], and generalizability (n = 16) [1,3,14,16,24,26,27,29–34,40,45,47].

Only a few studies included details regarding modeling testing: evaluation and testing (n = 9) [8,15,16,21,26,29,32,34,48], model calibration (n = 7) [12,15,16,31,35,41,48], and quality of calibration fit (n = 3) [12,15,48]. Stakeholder engagement in model development was only made explicit in one manuscript [2].

3.10. Study findings

Although the insights drawn by each study are contingent on the specific assumptions, parameterization, and data, we summarized the optimal strategies outlined by these 43 modeling studies. The optimal timing of pre-travel screening would be 0–1 day before departure, subject to test turnaround time [2,8,32,44,47]. Depending on the other measures implemented at the same time, the optimal length of effective quarantine after arrival would vary from 5 to 14 days [8,14,19,20,25,28,31–33,38,42,47,49]. While PCR is more sensitive than rapid antigen testing, the turnaround time (typically 2 days) for results would make rapid testing more effective for travel-related testing [8,20,23,45]. COVID-19 testing after arrival would reduce the quarantine period, with daily testing having the greatest impact [2,8,14,23,25,32,35,45,47].

In the four studies that assessed costs, one study estimated the costs of testing under different strategies in Chinese provinces and projected that the Guangdong province would bear the greatest costs due to the highest number of individuals taking tests before traveling [36]. Another study calculated the economic costs between two regions as the total costs of a “lockdown” that restricted human mobility, as well as the costs of deaths [24]. With limited mobility from an origin to a destination, the origin setting would experience higher costs associated with “lockdown” than the destination because infection cases would remain at the origin site, and economic production would be restricted; both regions would experience costs due to reduced travel and economic activities. With greater mobility, the destination would bear higher costs associated with “lockdown” following an increased number of infections due to arriving travelers. One study assessed the costs of staying home as socio-economic loss and found that higher socio-economic loss would be associated with a lower acceptance of staying home [26]. To mitigate the effects of lost earnings due to staying home, the study suggested that the government should provide compensation [26]. The fourth article found that a strategy that includes testing twice without quarantine would cost less on a per capita basis than a strategy with 14-day quarantine without testing because of a smaller number of infections [35]. Although detailed methods on the approach used were not included, this estimation assumed the government expenses are the sum of quarantine, testing, and treatment costs, minus any spending from travelers after quarantine [35].

4. Discussion

In a detailed review of 43 published travel-related COVID-19 modeling studies, we found that the focus of most analyses was on travel-related strategies to reduce COVID-19 cases without assessments

Table 2
Results of critical review.

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Arino et al., 2020 [1]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	17
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Chinazzi et al., 2020 [12]	Problem definition	–	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	–	Comparison with other results	–	9
	Modeling objective	✓	Model equations	–	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	–	Quality of calibration fit	✓	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	–	Software used	–					Conflicts of interest	✓	
Costantino et al., 2020 [13]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	–	Comparison with other results	✓	14
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Dickens et al., 2020 [14]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	12
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	–	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Hossain et al., 2020 [15]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	14
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	✓	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Lai et al., 2020 [16]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	20
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Linka et al., 2020 [17]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	13
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Mandal et al., 2020 [18]	Problem definition	–	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	11
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	–	Software used	–					Conflicts of interest	✓	
Arino et al., 2021 [19]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	17
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Ashcroft et al., 2021 [20]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	18
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Bays et al., 2021 [3]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	–	Comparison with other results	–	14
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	–	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	–	
Chen et al., 2021 [21]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	17
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	–	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Chowell et al., 2021 [22]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	15
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Clifford et al., 2021 [2]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	19
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	✓	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Dickens et al., 2021 [23]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	13
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Hu et al., 2021 [24]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	16
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Johansson et al., 2021 [25]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	19
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Kabir et al., 2021 [26]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	12
	Modeling objective	–	Model equations	✓	Model calibration	–	Report of quantitative results	–	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Kiang et al., 2021 [7]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	20
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Kwok et al., 2021 [27]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	11
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Leung et al., 2021 [28]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	15
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Lin and Peng, 2021 [29]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	✓	20
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Peng et al., 2021 [8]	Problem definition	–	High-level model visualization	–	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	13
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	–	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	–	Software used	✓					Conflicts of interest	✓	
Sachak-Patwa et al., 2021 [30]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	22
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
van der Toorn et al., 2021 [31]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	20
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Wells et al., 2021 [32]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	18
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Wilson et al., 2021 [33]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	16
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	✓			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	–	Software used	✓					Conflicts of interest	✓	
Yang et al., 2021 [34]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	–	15
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Zhong, 2021 [35]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	20
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Zhou et al., 2021 [36]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	12
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Zhu et al., 2021 [37]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	12
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	–	
	Model conceptualization	✓	Software used	–					Conflicts of interest	–	
Bays et al., 2022 [38]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	11
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	–	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	–	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	–	
Bisanzio et al., 2022 [39]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	14
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Chevalier et al., 2022 [40]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	–	Comparison with other results	–	13
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	–	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Guagliardo et al., 2022 [41]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	13
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Kamo et al., 2022 [42]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	14
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	–	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
Shah et al., 2022 [43]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	10
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	–	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	–	
Shen et al., 2022 [44]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	✓	14
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	–	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Steyn et al., 2022 [45]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	15
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	–	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	✓	
van Gemert et al., 2022 [46]	Problem definition	✓	High-level model visualization	–	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	13
	Modeling objective	✓	Model equations	–	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	–					Conflicts of interest	–	

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Table 2 (*continued*)

Author(s), year	Modeling development				Modeling testing		Modeling analysis		Other qualifications		Score (max score: 26)
Wells et al., 2022 [47]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	19
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	✓	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	✓	
	Modeling method	✓	Modeling code availability	✓			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Wong et al., 2022 [48]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	✓	Discussion about strategies and policies	✓	Comparison with other results	✓	21
	Modeling objective	✓	Model equations	✓	Model calibration	✓	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	✓	Parameter values and data sources	✓	Quality of calibration fit	✓	Structural insights	–	Limitations discussion	✓	
	Stakeholder engagement	–	Model assumptions	✓			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	✓	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	
Zou et al., 2022 [49]	Problem definition	✓	High-level model visualization	✓	Evaluation and testing	–	Discussion about strategies and policies	✓	Comparison with other results	–	14
	Modeling objective	✓	Model equations	✓	Model calibration	–	Report of quantitative results	✓	Generalizability discussion	–	
	Model scope	–	Parameter values and data sources	✓	Quality of calibration fit	–	Structural insights	✓	Limitations discussion	–	
	Stakeholder engagement	–	Model assumptions	–			Input sensitivity analysis	✓	Reproducibility discussion	–	
	Modeling method	✓	Modeling code availability	–			Output sensitivity analysis	–	Sources of funding	✓	
	Model conceptualization	✓	Software used	✓					Conflicts of interest	✓	

Note: This table shows the scores of critical review with one point assigned to each criterion met (max score = 26).
Abbreviations: ✓ = Met the criterion; (−) = Does not meet the criterion.

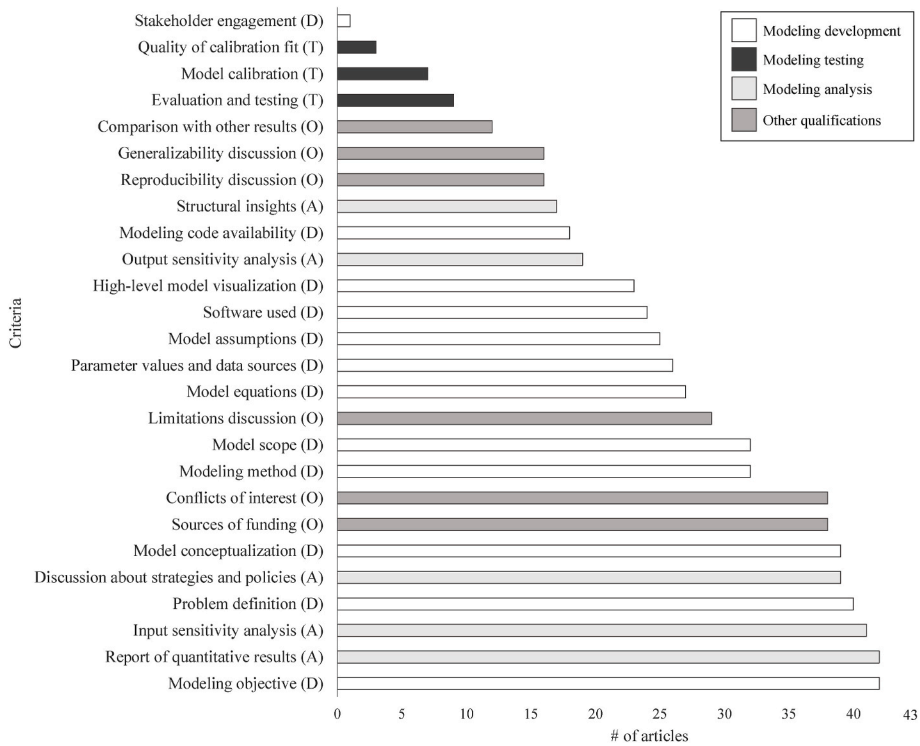

Fig. 2. Critical evaluation of the 43 modeling studies using standardized 26 criteria. The critical evaluation of 43 modeling studies used prespecified 26 criteria in four areas to assess the transparency and rigor of modeling approaches [9]: (1) *Modeling Development (D)*: problem definition, modeling objective, model scope, stakeholder engagement, modeling method, model conceptualization, high-level model visualization, model equations, parameter values and data sources, model assumptions, modeling code availability, and software used; (2) *Modeling Testing (T)*: evaluation and testing, model calibration, and quality of calibration fit; (3) *Modeling Analysis (A)*: discussion about strategies and policies, report of quantitative results, structural insights, input sensitivity analysis, and output sensitivity analysis; (4) *Other Qualifications (O)*: comparison with other results, generalizability discussion, limitations discussion, reproducibility discussion, sources of funding, and conflicts of interest.

of detailed clinical outcomes of COVID-19, more recently available strategies, or costs. The most frequently evaluated strategy was post-travel quarantine lasting up to 14 days, which could be shortened if combined with PCR or antigen testing at the end of quarantine. Although published articles considered the relevant strategies at the time, more recently available strategies have not yet been incorporated into published modeling analyses, including the use of antigen testing soon after arrival, improved ventilation during transit, and initiation of oral treatments for infected travelers [52]. Costs were rarely incorporated into the models, despite many analyses stating the importance of incorporating costs to examine the trade-offs between health benefits and budgetary burdens.

We found that modeling analyses included two distinct types of outcomes, depending on the interests and goals at the time of analysis. Individual-level outcomes were mostly used in research from early 2020, when policies focused on preventing any single case importation and keeping the location free from SARS-CoV-2. When focused on restricted settings, such as island nations and cruise ships [22,41,46] or examining "zero-COVID" policies [12,15,16,21,27,28,49], studies often used individual-level outcomes, such as estimating the number of infected travelers. In these types of settings, the importation of one infected individual would be influential for COVID-19 control policy. Population-level outcomes were included in more recent studies (since 2021), when many jurisdictions no longer attempted to eliminate COVID-19 importation. Studies more frequently incorporated these population-level outcomes to assess the impact of secondary transmissions among the destination communities when focused on European countries [2,30,47] and the US [2,7,43], where human mobility is considered to be an essential component of foreign policy and national economies [53] in comparison with Asian and Pacific island countries that emphasized maximum protection from COVID-19 importation.

The selection of strategies was influenced more by the availability of control measures and tools at a given time in the pandemic rather than specific policy interests and goals. Studies from early 2020 to 2021 included the strategies available at the time, such as travel restrictions [12–15,17,21,26,29], on-arrival PCR testing [3,18,33,37], quarantine without testing [1,13,17,19,21,26,33,37,49], and social distancing [8,16,22,35]. By contrast, analyses from later in the pandemic reflect that antigen testing and vaccination became more widely accessible and considered quarantine with frequent testing [7,20,23,25,31,32,34,38,45,47] and vaccination [28,30,44–47,49]. Nineteen of the published studies used individual-based strategies focused on international travel [1–3,20–23,25,26,28,31,33,34,37,38,40,42,45,47]. Other than border restrictions, we found no evaluations of population-wide strategies, such as improving ventilation or wastewater monitoring [54,55]. Of the 43 studies, only 13 included a domestic travel setting [7,12,15–18,29,36,39,43,44,48,49], despite the potential for travel-related transmissions to occur with in-country travel [56]. Given rapidly changing pandemic containment strategies, no published modeling analyses to our knowledge included more recent clinical and public health recommendations, such as the 5-day isolation period for COVID-19 cases in the U.S. with mask-wearing through day 10 [57] or the effectiveness of combinations of different vaccine brands and boosters [58].

Our findings suggest that modeling research does not always take practical implications into consideration; only five studies directly assessed practical implications of the modeling research. One study applied the model's findings to a quarantine and testing policy implemented for an off-shore oil company's employees and found that the modeled quarantine duration with additional testing on quarantine exit would reduce transmission risks [32]. Four analyses were used to support the findings of a policy report based on surveillance data [2,7,25,59], as well as policy decisions regarding introducing pre-departure testing [25,60] and reducing quarantine periods [25,52]. Additionally, only a few studies conducted evaluation (n = 9) [8,15,16,21,26,29,32,34,48] and calibration (n = 7) [12,15,16,31,35,41,48] of their models with real-world data. We also identified settings and parameters that were extremely simplified in some analyses, such as assumptions about or parameterizations of quarantine entry/exit and quarantine effectiveness that did not reflect real-world logistics or that relied on estimates that were unmeasurable with empirical data. Although every modeling study has hypothetical settings and limitations, model structure and parameterization should be built on the best possible domain knowledge and data, validated to empiric data when possible, and revised to address practical implications.

This critical review, using 26 pre-specified criteria, showed that most studies defined the modeling objectives, strategies, and problems, but the highest-scoring studies also clearly specified the modeling concepts and approaches specifically in the domain of model development. Substantial gaps were observed in terms of modeling evaluation and calibration in the domain of modeling testing, as well as community and policymaker involvement during modeling development. These lapses may reflect the rapid development of these models given the urgent public health needs, the absence of detailed individual-level data, and limited resources to revise the modeling approaches as new data became available. We identified sixteen studies that considered expanding the model to other situations [1,3,14,16,24,26,27,29–34,40,45,47] and sought reproducibility through publishing the model code (n = 16) [1–3,7,8,16,20,21,29–32,35,38,40,47]; however, most models were not revised or used iteratively. Publicly available modeling approaches could allow researchers to engage in dialogue with policymakers and community partners to advance modeling development and validate and modify the models with the latest empiric data for improved policy decision-making.

We have four key recommendations for future modeling analyses to advance modeling methods and realize evolving policy goals with updated strategies. First, open data sources provide robust and reportable data to populate models, yet only some papers used open flight and transportation data [2,12,13,15–17,29,39,49]. Using an Application Programming Interface (API) to connect a model with a data source and obtain real-time data, including publicly available real-time aviation data and COVID-19 infection cases at global and municipal levels, could provide estimates that more accurately reflect current trends [61–64]. Second, modeling methods should be fully documented and transparent, which has been a common shortfall in COVID-19 models [65]. For example, only 18 of 43 papers published the codes used for modeling on GitHub, the Open Science Framework (OSF), or Figshare [1–3,7,8,16,20,21,25,29–33,35,38,40,47]; making code publicly available would allow others to apply, validate, and adapt the models to the rapidly evolving landscape of SARS-CoV-2 or other pathogens and inform policymaking in a timely manner. Third, the existing literature rarely included costs, even though costs are essential to understanding the value of public health policies and clinical strategies. Although it could have been challenging to define costs early in the pandemic, future modeling should include cost-effectiveness analyses to inform public health decision-making. Lastly, published model-projected outcomes should be directly compared with emerging real-world data to assess model quality, when data allow.

This review has several limitations. This is not a systematic review and does not include non-English reports. We did not consider extensive variations of search terms or include other related terms such as "mask-wearing," "social distancing," "do not board," or "travel restriction." We found that very few analyses focused on ship transport, ground transport, and land border crossings; these forms of travel and border crossings are likely to have unique features that could influence travel-related control strategies. This review provides a complementary approach to an existing review on COVID-19 travel-related modeling, which applied the GRADE methodology for modeling analyses that assessed quarantine and isolation before February 2021 [10]. In contrast, this scoping review includes a summary of modeling papers over a longer time period as the pandemic evolved, as well as a critical assessment of the modeling approaches using prespecified criteria [9].

Domestic and international travel is recovering from the global downturn [66]; nimbler models with the flexibility to incorporate updated input estimates are critical for COVID-19 and other emerging pathogens. Models should tackle uncertainties in SARS-CoV-2 variants of concern that might elude immune responses and consider interactions with other respiratory and travel-related diseases. Future modeling work should incorporate detailed and representative data, develop transparent modeling methods, and align with available travel-related public health policy goals. Moreover, the world faces competing public health demands and must consider and address multiple travel-related infectious diseases, including Zika, Ebola, and mpox [67]. Scientists should develop and revise models in collaboration with communities, healthcare providers, public health workers, and policymakers, ensuring that models include science-driven, feasible strategies and provide evidence to inform the most clinically effective and high-value policies.

5. Conclusion

In summarizing and critically evaluating the approaches taken by 43 published COVID-19 travel-related modeling analyses, we identified areas of future focus for COVID-19 modeling research. This review underscores the importance of using open sources for data, enhancing the transparency of modeling methods to utilize, validate, and adapt the models, and expanding modeling approaches to include cost-effectiveness analyses that can be used to examine public health needs and uncertainty in emerging travel-related diseases, and develop high-value, travel-related policies.

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CRediT authorship contribution statement

Satoshi Koiso: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft. **Eren Gulbas:** Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Writing – original draft. **Lotanna Dike:** Writing – review & editing. **Nora M. Mulroy:** Data curation, Methodology, Project administration, Resources, Writing – review & editing. **Andrea L. Ciaranello:** Funding acquisition, Writing – review & editing. **Kenneth A. Freedberg:** Funding acquisition, Writing – review & editing. **Mohammad S. Jalali:** Methodology, Writing – review & editing. **Allison T. Walker:** Writing – review & editing. **Edward T. Ryan:** Funding acquisition, Writing – review & editing. **Regina C. LaRocque:** Funding acquisition, Writing – review & editing. **Emily P. Hyle:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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